Magnetic-field-enhanced rf argon plasma for ionized sputtering of copper

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(Received 13 June 1997; accepted for publication 29 July 1997)

A multipole magnetic field was used to increase the ion density of an inductively coupled rf (13.5 MHZ) argon plasma for ionized magnetron sputtering of copper (Cu). Langmuir probe measurements showed an increase of plasma density over a factor of 2 with the application of the magnetic field. At an argon pressure of 15 mTorr and a rf power of 600 W, an ion density of 1.2×10^{12} ions/cm^3 was achieved. When this plasma was applied to ionize the magnetron sputtered Cu vapor, a high emission intensity ratio from the Cu^+ ion line to the Cu neutral line was observed from the optical emission spectroscopy, suggesting a high ionization fraction for the sputtered Cu vapor. © *1997 American Institute of Physics.* [S0003-6951(97)05038-9]

One of the challenges for the continuous reduction of semiconductor devices to subquarter micron regimes is to uniformly deposit metals (Al, Cu) films into deep trenches with a high aspect ratio for contact and interconnect applications.[1,2] Conventional sputtering becomes insufficient because of its broad angular distribution of the sputtered atom flux, which leads to pinch-off near the opening of the trench and void formation in the films during the trench filling.

Recently, ionized sputtering was proposed to solve the aforementioned issues.[3–7] In ionized sputtering, a high-density argon plasma is generated between the sputtering target and substrates, and the sputtered metal vapor atoms become ionized when they traverse the high-density argon plasma region. When a negative dc bias is applied to the substrate, the positive metal ions are attracted toward the substrate and deposit on the bottom of the trenches with a good directionality. At the same time, resputtering by the metal or argon ions can help to minimize the pinch-off at the top of the trench.

In this letter, we report results of a study using a multipole magnetic field to enhance an inductively coupled rf argon plasma for ionized magnetron sputtering of copper, including Langmuir probe and optical emission spectroscopy measurements of plasma density and Cu vapor ionization.

The experimental apparatus is shown in Fig. 1. An aluminum chamber of 48 cm diam and 54 cm height was used. The chamber has a base pressure of 8×10^{-7} Torr. A dc-magnetron sputtering source was installed from the top of the chamber. The Cu vapor was produced by sputtering of a Cu target of 5 cm diam. A rf antenna was installed from the top of the chamber and located approximately 5 cm below the sputtering source. The antenna, consisting of one and one-half turns of aluminum tubing (outside diameter 6 mm), has a diameter of approximately 15 cm.

A multipole magnetic field was produced by a set of alternating rows of north and south pole permanent ceramic magnets placed around the circumference of an aluminum ring (25 cm diam) inside the vacuum chamber. Each row is composed of four permanent magnets (diameter and length of 2.5 cm, and 1 kG at the surface). A total of 12 rows were used. The alternating rows of magnets generate a line cusp magnetic configuration in which the magnetic-field strength B is a maximum near the magnets and decays rapidly with distance into the chamber. Hence, most of the plasma volume is virtually field free.

The argon plasma densities were determined by using a rf compensated Langmuir planar probe, which was located at the center of the multipole magnetic ring and about 4 cm below the rf coils. The ion densities were calculated from the ion saturation currents of the $I-V$ traces from the probe measurements. The optical emission spectra were recorded by using a 0.5 M scanning spectrometer with a photodiode array. The emission was collected by a 2.5 mm optical fiber through a quartz viewport looking at the center of the antenna. A 1200 groove/mm grating (0.02 nm resolution), was used to disperse the light.

Figure 2 compares the ion densities as a function of rf power for argon plasma with and without the multipole magnetic field. An argon pressure of 15 mTorr was used for all the measurements. Without the multipole magnetic field, as shown by the lower curve in Fig. 2, the ion density of the argon plasma at 100 W is about 1.3×10^{11} ions/cm^3, and it increases slowly with rf power. When the multipole mag-

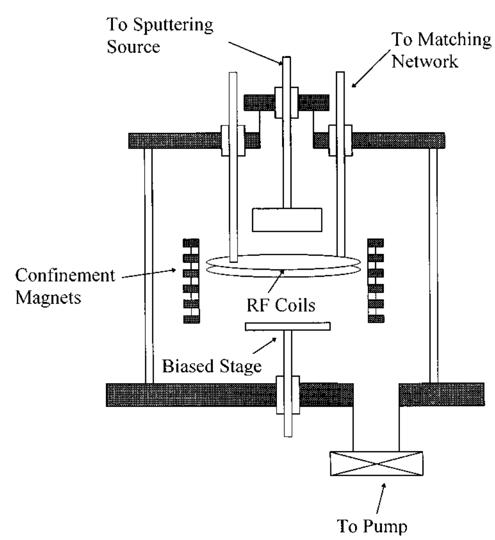

FIG. 1. A schematic drawing of the apparatus used for this study.

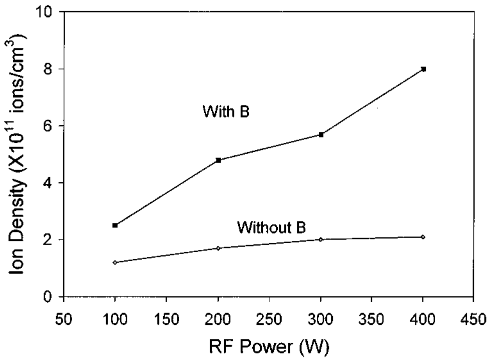

FIG. 2. Comparison of argon ion densities from Langmuir probe measurements as a function of rf power with and without a multipole magnetic field. The measurements were taken at an Ar pressure of 15 mTorr.

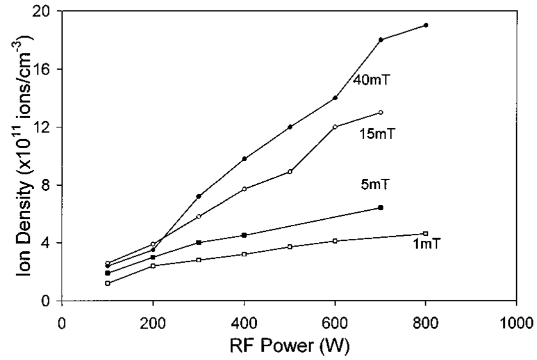

FIG. 3. Ion densities of argon plasma as a function of rf power at argon pressures of 2, 5, 15, and 40 mTorr. A multipole magnetic field was used during these measurements.

netic field is used, the plasma intensity significantly increases. This is indicated by a marked intensification of visible light emission and confirmed by Langmuir probe measurements.

The argon ion densities versus rf power with the multipole magnetic field are represented by the top curve in Fig. 2. At 100 W, the plasma density increases to about 2.5×10^{11} ions/cm^3, which is about 2.5 times larger compared to that of the plasma without the magnetic field. At 400 W, the ion density reaches approximately 8.2×10^{11} ions/cm^3, which is about four times larger than that without the magnetic field.

Previous investigators have shown that plasma ion densities of $5-10\times 10^{11}$ ions/cm^3 can be generated by using two turns of rf coils at power ranging from 200 to 500 W and an argon pressure around 20 mTorr.[4,5] In this study, the plasma density is around 3×10^{11} ions/cm^3 under similar conditions without applying the magnetic field.

The increase of the rf argon plasma density with the application of the multipole magnetic field is believed to be mainly caused by the confinement of energetic electrons in the multipole magnetic field. It has been reported that high-energy electrons in a hot filament Ar plasma can be effectively confined by using a magnetic field.[8] As these energetic electrons are directly responsible for Ar ionization, their enhanced confinement yields an increase in Ar plasma density. Another factor that may also contribute to the increase of the plasma density is the reduction of the plasma volume when the multipole magnets are used.

Figure 3 shows the densities of argon plasma at different argon pressures versus rf power when the multipole magnets were used. These results are similar to previous observations by different research groups.[3,4] The ion density increases with rf power and argon pressure.

Optical emission spectroscopy was used to make a qualitative estimate of how the ratio of Cu ions to Cu neutral concentration varies as discharge parameters vary. This approach has been used in similar studies to make Cu ionization fraction estimates.[9] In general, the intensity of a given emission line is proportional to the concentration of the species and the excitation rate of the transition in question. The ratio of intensity of a copper ion line to a copper neutral line is then proportional to the ionization ratio, provided the ratio of the excitation rates is constant over the range of discharge conditions of interest. The constancy in the ratio of the excitation coefficients over a range of operating conditions prevails if the electron energy distribution function does not vary.

In this investigation, the electron energy distribution function is assumed to be constant with the changes in power at constant pressure. This assumption is based on the uniform density discharge model, which asserts that the electron energy distribution is independent of both plasma density and input power.[10] This assumption is further supported by Langmuir probe measurements, which indicate that the electron temperature does not vary appreciably with increasing discharge power at fixed pressure.

For this study, the light-emission intensity ratio of the copper ion line at 213.6 nm to the copper neutral line at 216.5 nm is used as a measure of the variation in the ionization fraction of sputtered copper as a function of rf excitation power. Figure 4 shows a plot of the variations in the emission intensity ratio of the copper ion line to the copper neutral line at a magnetron sputter power of 300 W as a function of rf power at 10 and 20 mTorr. Both curves demonstrate an increase of the emission intensity ratio with rf power at fixed Ar pressure, suggesting a higher ionization fraction of Cu

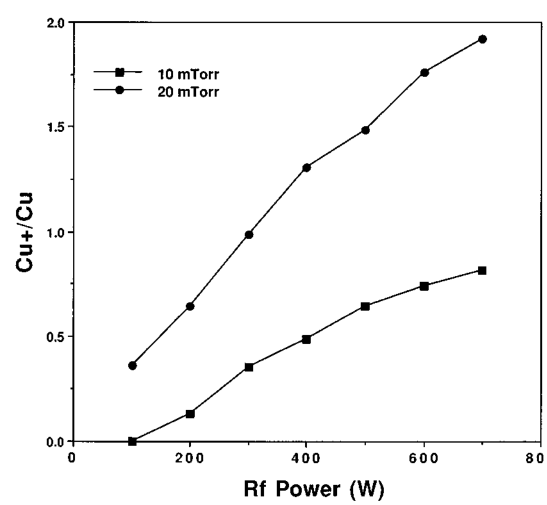

FIG. 4. A plot of the emission intensity ratio from the Cu^+ ion line (213.5 nm) and Cu neutral line (216.5 nm) as a function of rf power at pressures of 10 and 20 mTorr, respectively.

vapor at larger rf power. As the electron temperature of the Ar plasma is assumed to be constant with the rf power at fixed pressure indicated from the Langmuir probe measurements, the increase of the ionization fraction of Cu vapor is ascribed entirely to the enhancement of electron density at higher rf power, as shown in Fig. 3.

The ratio of emission intensity increases with Ar pressure at fixed rf power, as shown in Fig. 4, indicating a larger ionization fraction of Cu vapor at higher Ar pressure. This is consistent with the observations from other groups where the metal vapor ionization fractions were determined by using an energy analyzer or a microbalance.[4,5] Although electron temperature is expected to decrease as Ar pressure increases, the increase of electron density at higher Ar pressure (Fig. 3) is expected to offset any electron temperature reduction, thereby, yielding the observed net increase in the Cu vapor ionization fraction.

In summary, a multipole magnetic field was demonstrated to enhance the intensity of an inductively coupled rf argon plasma for ionized sputtering of Cu. Confinement of energetic electrons by the multipole magnetic field is believed to be the main cause for the enhancement of plasma density. The optical emission measurements showed a high emission intensity ratio from the Cu^+ ion line and Cu neutral line.

This research was supported by the National Science Foundation (NSF) under Grant No. EEC-8721545.

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